

Visualization of Dyeing based on Diffusion and Adsorption Theories

Yuki Morimoto
Kyushu University
reo@verygood.aid.design.kyushu-u.ac.jp

Reiji Tsuruno
Kyushu University
tsuruno@design.kyushu-u.ac.jp

Masayuki Tanaka
The University of Tokyo
tanaka.research@gmail.com

Kiyoshi Tomimatsu
Kyushu University
tomimatu@design.kyushu-u.ac.jp

Abstract

This paper describes a method for simulating and visualizing dyeing based on weave patterns and the physical parameters of the threads and the dye. We apply Fick's second law with a variable diffusion coefficient. We calculate the diffusion coefficient using the porosity, tortuosity, and the dye concentration based on the physical chemistry of dyeing. The tortuosity of the channel was incorporated in order to consider the effect of the weave patterns on diffusion. In this model, the total mass is conserved. We describe the cloth model using a two-layered cellular model that includes the essential factors required for representing the weft and warp. Our model also includes a simple dyeing technique that produces dyeing patterns by interrupting the diffusion of the dye in a cloth using a press. The results obtained using our model demonstrate that it is capable of modeling many of the characteristics of dyeing.

1. Introduction

Dyeing is a traditional way to impart color onto cloth. Visual simulation of dyeing is important for representing garments using computer graphic images and also for drawing simulations. The liquid penetration onto cloth is a complicated phenomenon from both a scientific and physical standpoint. This paper presents a system that considers the physical parameters used to simulate dyeing on cloth. The pattern and color of the dyed cloth is an outcome of the physical properties of the dye and the fabric. Woven cloth also has legal patterns. Dying on fabric shows different results from that of liquid diffusion on paper. Some characteristic features of liquid diffusion on cloth that are influenced by weave patterns, such as thin spots and mottles are shown in Figure 1. We show dye diffusion images along with other specific characteristics of dyeing that can be obtained using

our method. In actual dyeing, a wet cloth is used to prevent color heterogeneity. This paper presents a system that considers the physical parameters of dyeing onto a wet cloth. In real dyeing, there are some other ways to prevent color heterogeneity, including using a catalyst and controlling the adsorption ratio. We could not model each chemical technique accurately, however we adopted some typical models of adsorption isotherms to simply show adsorption. These approaches can contribute to improving the simulation of pigment deposition in non-photorealistic rendering (NPR) research.

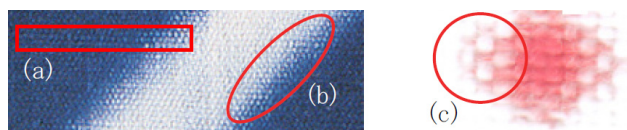


Figure 1. Some characteristic features of dyeing. (a) thin spots, (b) bleeding ("nijimi" in Japanese), and (c) mottles.

2 Outline of dyeing

The purpose of dyeing is to change the color of a cloth, that is, to bond dye tightly to fabrics. The three key elements of dyeing are the cloth, the dye, and the dyeing technique; each element has many different types [4].

Cloth is a fabric woven from threads. The threads are composed of fibers. Dye diffuses along the fibers in a cloth; the directional characteristics of the thread thus exert a strong influence on the diffusion of dye in the cloth. The two-directional thread structure of woven cloth is known as the weft and warp. The type of cloth is classified according to its weave pattern, the most well-known being the plain-weave pattern, in which the weft alternately goes over and

under the warp. However, in addition to the weave pattern, there are other factors that affect dyeing, such as the interval between fabrics. Narrow intervals between fabrics prevent dyeing [12] [15] [17] [24].

Dyeing techniques are important for representing dyeing as an art form. There are two ways to make dyeing patterns, namely drawing and preventing dye diffusion. We describe the following common dyeing process for preventing diffusion using the example shown in Figure 2. 1) Prepare the cloth by cleaning it. 2) Create a pattern by preventing parts of the cloth from being dyed. There are two techniques for achieving this, namely tie-dyeing, which imparts pressure to the cloth by folding and sewing, and batik, which involves coating the cloth with wax. 3) Wet the cloth with water. 4) Dip the cloth in the dye compound. 5) Dry the cloth and open it. 6) Wash the cloth to remove dye pigments that are not firmly attached to the fabrics, and 7) dry it. After drying, the dyeing process is completed.

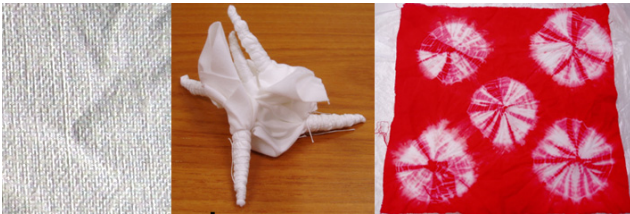


Figure 2. Outline of the real dyeing process. A left image shows a real cloth, a center image shows the tied cloth, a right image shows the tie-dyed cloth.

3. Related works

Methods for simulating painting implements and drawing strokes are being advanced in the field of NPR. Some studies have been done in this area into watercolor painting and Chinese ink painting, both of which involve diffusion of pigment in paper. Curtis et al.[6] presented a method for simulating watercolor effects such as dry-brushing, intentional backruns, and flow patterns. Chu and Tai[5] provided a novel method that simulates drawing of a fluid on absorbent paper by solving the lattice Boltzmann equation in real time. Kunii et al.[11] used partial differential equations (PDE) using a variable diffusion coefficient to model the phenomenon. Their PDEs for water spreading in dry paper and pigment movement in water are essentially Fick’s law of diffusion. A variable coefficient is also important to describe the dyeing phenomenon [16]. These methods do not describe diffusion in compressed cloth and paper seen in dyeing techniques and they mainly focus on dry paper using two-dimensional plane data. A two-dimensional cloth

model is inadequate for representing dye diffusion since woven cloths have an intentional three-dimensional structure consisting of threads. Our dye diffusion model is physically defined as dip dyeing. The variable diffusion coefficient is calculated using the theory of dyeing in our two-layered cloth model.

There have been several studies of methods for simulating painting techniques on cloth, including the batik technique. Wyvill et al.[22] presented an algorithm for simulating the cracks that occur in batik. Their method is capable of producing convincing patterns that capture many of the characteristics of the crack patterns found in real batik cloth. In addition, Drago et al.[8] performed simulations of canvas used for easel paintings. Their work simulates real woven canvases that have weaving patterns and canvas aging. However, the texture of the cloth was not included in Wyvill’s algorithm and diffusion in cloth was not considered in either Drago’s or Wyvill’s research.

There have also been some studies on visualization methods of cloth. These studies attempted to represent interwoven threads and to model the interaction of light with the threads of the cloth in detail using the bidirectional reflectance distribution function (BRDF) or other representations [3][21][23]. In this study, however, we do not use such a light reflection model; instead, we use the procedural thread texture model by Adabala et al.[2] to represent the cloth.

Previous visual modeling of patterns include reaction-diffusion models of animal coat patterns [Turk1991] and sea shell pigmentation [10], clonal mosaic models of animal coat patterns [20], diffusion-limited aggregation models of lichens [7], and physically based models of bark textures [14][1]. However, since these phenomena all involve some reactive dyestuffs, they are comparatively complex phenomena and are difficult to model numerically. Thus, in this study, we focus on dyeing that occurs by physical diffusion, and do not consider the effect of chemical reactions.

4. Computer generated dyeing

4.1. Cloth model

We represent the cloth by cells (see Figure 3). We define two kinds of cells, namely a cloth cell, and a diffusion cell. In cloth cells, parameters such as the weft or warp, the vertical position relative to the weave patterns, the size of threads and gaps, and other physical diffusion factors specific for each thread are defined. Each cloth cell is subdivided into several diffusion cells and these diffusion cells are then used to calculate the diffusion.

Initially, cloth cells are defined by the size of the warps and wefts, which can be assigned arbitrarily. They are then

arranged in the cloth at intervals equal to the spacing of gaps. Two layers are prepared as the weft and warp for cloth cells. Next, a defined weave pattern determines whether each cloth cell is orientated up or down. Diffusion cells are also arranged in the cloth size and two layers are formed. Their properties are defined in reference to the cloth cell in the layer that they are in. Each diffusion cell can have only one of two possible orientations (parallel to the x and y axes) as the fiber's orientation in its layer. Gravity is considered to be negligible in our dye diffusion model since the dye is usually a colloidal liquid; this enables us to calculate the diffusion without considering the height in the cloth. There is thus no necessity to arrange diffusion cells in three-dimensional space, making it is easy to consider the connection between threads. The effect of height is considered in our model only for cloth rendering.

The legal weave patterns can be represented using the cell-based cloth model. However, it is not intended to provide a more detailed representation on the small fiber level. In an actual fabric, the threads of the cloth are very small and the dyeing characteristics of each thread become highly significant. Consequently, we use the cloth cell model to display the cloth properties.

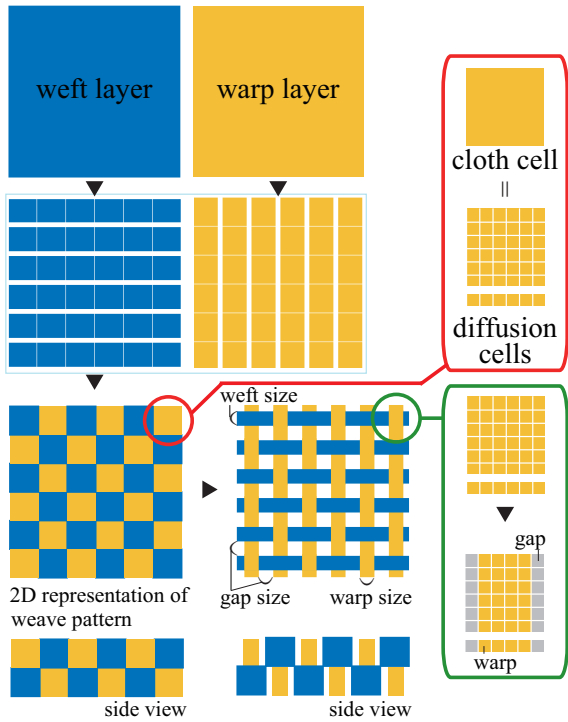


Figure 3. The example of cloth cells with plain weave.

4.2. Dye diffusion model

In our method, Fick's second law[9] is used to simulate dye diffusion in a wet cloth:

$$\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left(D \frac{\partial \phi}{\partial z} \right) \quad (1)$$

where ϕ is the diffusion density, t is the time, D is the diffusion coefficient, x is the displacement along the x -axis, y is the displacement along the y -axis, and z is the displacement along the z -axis. We discretize Eq. 1 to obtain

$$\frac{\Delta \phi_{i,j}}{\Delta t} = \frac{1}{\Delta d} \left\{ D_{i+1/2,j,e} \frac{\phi_{i+1,j,e} - \phi_{i,j,e}}{\Delta d} + D_{i-1/2,j,e} \frac{\phi_{i-1,j,e} - \phi_{i,j,e}}{\Delta d} + D_{i,j+1/2,e} \frac{\phi_{i,j+1,e} - \phi_{i,j,e}}{\Delta d} + D_{i,j-1/2,e} \frac{\phi_{i,j-1,e} - \phi_{i,j,e}}{\Delta d} + D_{i,j,(e+a)/2} \frac{\phi_{i,j,a} - \phi_{i,j,e}}{\Delta d} \right\} \quad (2)$$

where i and j are the x -axis y -axis positions of the diffusion cells respectively, and e, a indicate which layer a diffusion cell belongs to, where e is the weft layer and a is the warp layer. Δd is the distance interval between diffusion cells. D is defined as the diffusion coefficient between diffusion cells. The total mass is conserved theoretically. We define the size of diffusion cells to be the same as the pixel size. Each diffusion cell has various parameters associated with it; these parameters include its weft layer or warp layer, fiber or gap (i.e., no fiber), orientation (either up or down), position, porosity, and tortuosity. Porosity is defined as the ratio of void volume in a thread fiber. Tortuosity denotes the degree of twist, so that the smaller the value of the tortuosity is, the larger the twist is. We define three kinds of tortuosities in our method: one is the twist of the thread (τ_1), another is the position of the thread, including its orientation in the weave pattern (τ_2), the other is from the different orientations of fibers in neighboring diffusion cells (τ_3). Each of these tortuosities has values in the range (0, 1]. τ_1 is defined in each thread. τ_2 is determined by the connection between neighboring diffusion cells, whether they are in the same layer, whether they contain fibers, and whether their orientation is up or down. τ_3 has five different conditions (I: two fibers are in different layers, II: two fibers are in the same layer and lie perpendicular to each other, III: fiber and gap, IV: gap and gap, V: two fibers are in the same layer and lie parallel to each other) which depend on factors such as the layers that neighboring diffusion cells are located in and their porosity. Figure 4 shows the connection between diffusion cells with τ_3 . In Figure 4, white cells represent gaps in the warp layer. When the diffusion cell (i,j,e) is the target, τ_3 is defined by the following colored lines. (blue: I, orange: II, purple: III, green: IV, red: V.) Finally, the tortuosity of a cell T between diffusion cells is defined as follows:

$$T = \tau_1 \tau_2 \tau_3 \quad (3)$$

The diffusion coefficient is calculated between diffusion cells using the following equation that is based on the Weisz-Zollinger model[16] in accordance with our definition for T :

$$D = D_0 P T (\phi_0 / \phi) \quad (4)$$

where P is the porosity that can have any value in the range (0, 1], ϕ_0 denotes the dye concentration in the external solution when equilibrium is achieved and is specified arbitrarily. D_0 is the diffusion coefficient in free water and is calculated according to the following equation: [18]

$$D_0 = 3.6 \sqrt{76/M} \quad (5)$$

where M denotes the molecular mass of the dye. The volume capacity of the dye absorption in the diffusion cell V_d is determined by the ratio of fiber ($1 - P$) in the diffusion cell according to the following expression:

$$V_d = (1 - P) V_{max} \quad (6)$$

Also, the maximum amount of dye adsorption (fixing dye) into fibers (A_d) is calculated each time step by adsorption isotherm based on the dyeing theories used in our model [13], [19]. Figure 7 shows representative behavior of these typical adsorption isotherms. If we use the Freundlich equation (Figure 7 (b'')) in our system, we can define A_d as:

$$A_d = k \phi^b \quad (7)$$

where k is a constant, and b is a constant that lies in the range (0.1, 1). If $b = 1$, eq 7 become a linear equilibrium as shown in Figure 7 (a''). If we use the Langmuir equation (Figure 7 (c'')) in our model, we can defined A_d as:

$$A_d = \frac{V_d K_L \phi}{1 + K_L \phi} \quad (8)$$

where K_L is the equilibrium constant. The resulting images are shown in Figure 6 and are calculated using these adsorption isotherms. The amount of dye adsorption is calculated using the arbitrary adsorption coefficient D_{ab} according to eq 2. Since real dye stains cannot easily be washed away by water, we can assume that adsorption is a one-way process and that the amount of adsorption is less than V_d and A_d . Another parameter B that denotes the volume ratio in the range (0, 1] is used to simulate dyeing patterns. It prevents dyeing in the pressed area of the cloth and is used to represent the dyeing patterns of certain dyeing techniques. Curtis et al. [6] used a similar method in which the paper affects fluid flow to some extent for watercolor and by doing so generates patterns. But the effect of this phenomenon is not as pronounced as that of dyeing patterns. In our method, we use the amount of dye that is not absorbed by the fiber to calculate the total amount of dye in the diffusion cell. The

total amount of dye in a diffusion cell V is defined by V_u and V_d , where V_u is the dye capacity minus the amount of dye absorbed in the diffusion cell.

$$V_u = V_{max} P (1 - B), \quad V = V_u + V_d \quad (9)$$

In actual dyeing, the distribution of B is determined by the artist. We calculate the distribution of B based on the normalized average RGB values in an image.

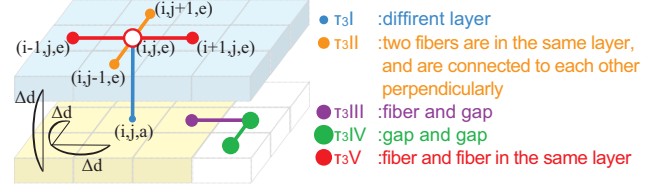


Figure 4. Connection between diffusion cells with tortuosity.

4.3. Visualization of the dye and cloth

Applying the algorithm described in Section 4.2 gives the dye dispersion. This algorithm can be used to determine the basic color of the diffusion pixels. We determine the basic colors by applying linear interpolation to the highest and lowest color values of a real image of a dyed cloth. In order to represent the dye, other color values can be added to determine the color from a real image of a dyed cloth. In this way, the pigment variations in dye stains are obtained.

We use a method that determines the cloth's texture by mapping the texture using the yarn's shadow [2]. The texture of yarn is produced by its tightness or roughness. Finally, the texture of the cloth is multiplied by the color of the dye. To model the fact that a high light reflectance renders the cloth's texture invisible, the brightness of the cloth color depends on the brightness of the color from the dye diffused at each diffusion cell.

5. Result

The results of our simulation are shown in Figs. 5, 6, 8, 9, 10, while Table 1 gives the parameters used. Figure 5 (d) shows mottles similar to those in Figure 1 (c). This shows that mottles are formed with not just when the value of $\tau_3 I$ is small but they are also produced by the two-layered model. Figures 5 (f) and (g) show the results for random P , while Figure 5 (e) shows the result for random τ_1 . Some thin colored threads can clearly be seen in Figure 5 (f). We find that P has more effect on the final appearance than τ_1 . Figure 5 (b) shows the result obtained when a high absorption coefficient is used; in this result, the initial dyeing area

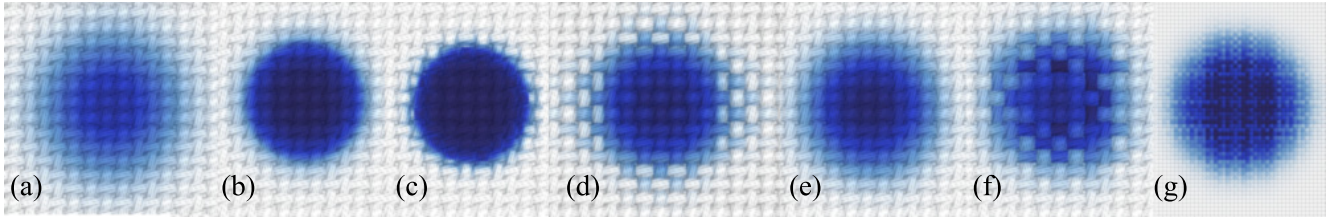


Figure 5. Computer generated dye stains with various parameters including T, P, D_{ab} . Total number of time steps is 5000.

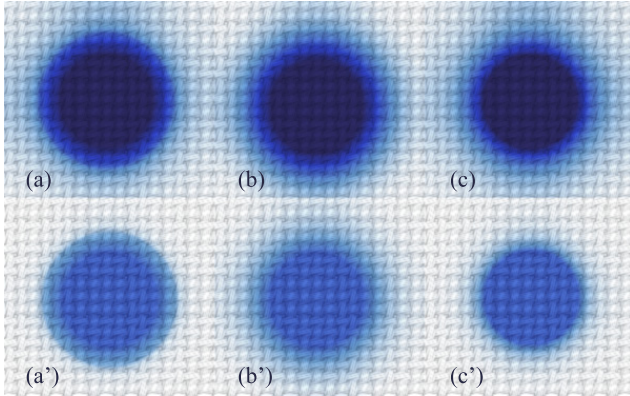


Figure 6. Comparison of simulations with some adsorption isotherms. Total numbers of time steps is 50000.

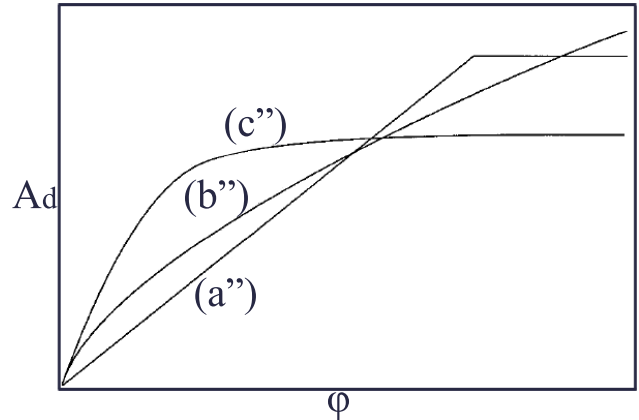


Figure 7. Behavior of some typical adsorption isotherms.

seems to contain a lot of dye. Figure 8 shows the effect of different kinds of weave patterns having identical parameters on dye diffusion. In this calculation a small value of $\tau_3 I$ was used, similar to Figure 5(d).

Figure 6 shows results calculated using some adsorption isotherms as shown in Figure 7. (a) is the result obtained using the Freundlich model (eq 7) where $b = 1, k = 1$, (b) is the result obtained using the Freundlich model (eq 7) where $b = 0.3, k = 1$. (c) is the result obtained using the Langmuir model (eq 8). (a'), (b') and (c') show only the absorbed dye densities of (a), (b) and (c), respectively. In this comparison, we can observe the effect of the kind of adsorption isotherm has on the results obtained. In the results obtained using the Freundlich model, the dye diffused and the dye is absorbed over a large area. In the results obtained using the Langmuir model, the dye diffused and the dye is absorbed over a small area in the vicinity of the initial area that the dye is applied; this demonstrates that the adsorption ratio is higher than the other cases in which the dye concentration is low.

There are obvious differences in the patterns obtained for different weave patterns that are caused not just by differences in the rendering cloths, but also by the number of

diffusion cells having low τ_2 . However, the effect of τ_2 on dye diffusion is not so large.

Figure 9 shows a comparison of a simulation for simple dyeing techniques and an image of a real dyed cloth. This pattern is called "seikaiha" and it is a traditional Japanese pattern. The image input for B can represent patterns produced by preventing diffusion that have never been considered in previous studies. Figure 10 shows the simulation of seikaiha (the same case as that for Figure 9) for different time steps.

6. Conclusion and future work

We have presented an improved diffusion equation that can take into account different weaving patterns, uneven diffusion coefficients, and different pressures for a tie-dyeing simulation. We used a physical theoretical model to calculate the diffusion coefficients, the diffusion coefficients in the water and the absorption rate. Additionally, we considered the porosity, tortuosity, and capacity of the yarns to simulate dyeing in a cloth that can account for many of the features of dyeing.

Our future goals are to simulate mixing colors, produce

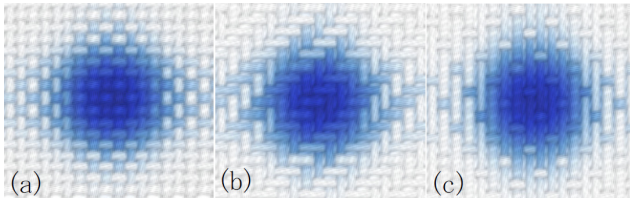


Figure 8. The differences between dye stains on different weave patterns. (a) Plain weave, (b) diagonal weave, (c) satin weave. Total number of time steps is 5000 in these images. Computational time of (a) is 6 min 15 sec.

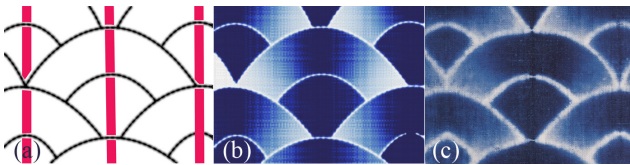


Figure 9. Simulation of a simple dyeing technique. Red region in (a) is distribution of the dye, while the black region is the pressure distribution. (b) is the result with (a), (c) is a real dyed cloth showing the seikaiha pattern.

an interactive simulation of dyeing a 3D cloth topology, model the effect of fluff on cloth, incorporate other dyeing techniques, and improve the interface of these systems. We would like to simulate tie-dyeing techniques, including folding, tying with threads and sawing, by manipulating the 3D cloth topology. In this study, we did not consider the effect of fluctuations in the properties of threads. However, these effects could make the representation of cloth more natural. In this study, we were not able to simulate the drying process since the dye is treated as consisting of water and pigments in the simulation. Also, it is necessary to consider the orientation of local fibers for detailed simulation of diffusion. In our model, we can define the orientation using with the diffusion coefficient. However, this method does not reflect the local orientations to the diffusion coefficient in a physical manner. These are the limitations of this work. We intend to verify if these effects are significant or not, and if they are significant, we intend to develop a new simulation that takes them into account. One of our goals in simulating dyeing on a dry cloth is to develop a diffusion system that can take capillary flow into account. The rendering of the cloth could be enhanced by modeling the interaction of light with the threads and taking the 3D cloth topology into account.

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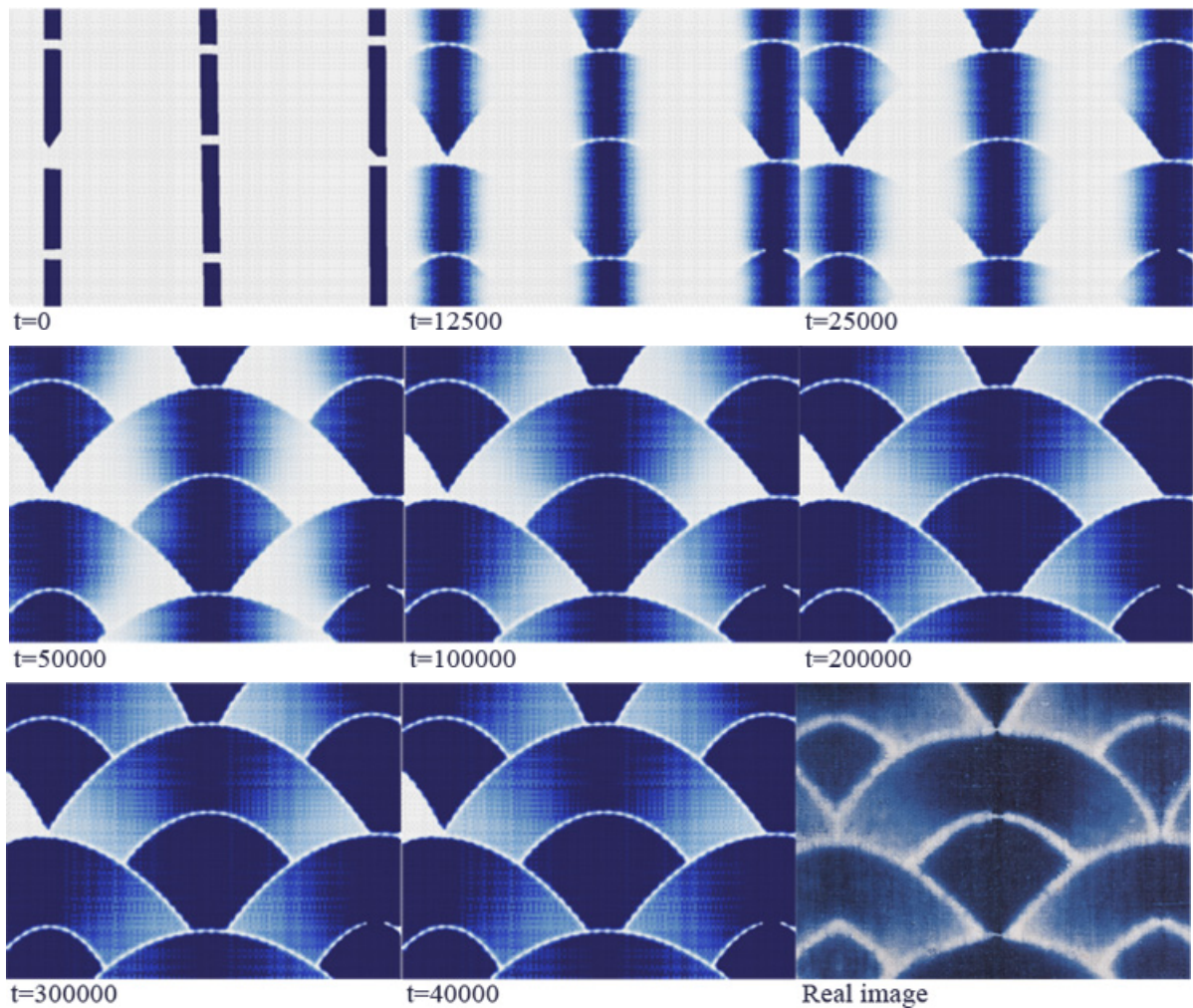


Figure 10. The simulation of seikaiha along the time step.

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Common factors									
size of threads, gaps					8, 2 (pixels) (2, 1 in Fig. 5(g), 4, 1 in Fig. 9(b))				
D_0					1.93 (mm^2/h)				
Δt					0.0005 (h)				
Δd					0.05 (mm)				
τ_2					0.47 (ratio)				
IV					1 (ratio)				
Dye distribution					Circle with 30 (pixels)				
Initial amount of dye					1.0V				
The number of diffusion cells					200*200*2 (800*600*2 in Fig. 9(b))				
Others	I	II	III	V	τ_1	P	D_{ab}	Adsorption isotherm	Weave pattern
Fig. 5(a)	1	1	1	1	1	0.5	0	(a'') in Fig. 7	Plane weave
Fig. 5(b)	1	1	1	1	1	0.5	$0.01D_0$	(a'') in Fig. 7	Plane weave
Fig. 5(c)	0	0.05	1	0	1	0.5	0	(a'') in Fig. 7	Plane weave
Fig. 5(d)	.005	0.005	0.005	1	1	0.5	0	(a'') in Fig. 7	Plane weave
Fig. 5(e)	1	1	0	1	$0.5r$	0.5	0	(a'') in Fig. 7	Plane weave
Fig. 5(f)	1	1	0	1	1	$0.5r$	0	(a'') in Fig. 7	Plane weave
Fig. 5(g)	1	1	0	1	1	$0.5r$	0	(a'') in Fig. 7	Plane weave
Fig. 6(a)	1	1	1	1	1	0.5	$0.01D_0$	(a'') in Fig. 7	Plane weave
Fig. 6(b)	1	1	1	1	1	0.5	$0.01D_0$	(b'') in Fig. 7	Plane weave
Fig. 6(c)	1	1	1	1	1	0.5	$0.01D_0$	(c'') in Fig. 7	Plane weave
Fig. 8(a)	0.01	0.01	0.01	1	1	0.5	0	(a'') in Fig. 7	Plane weave
Fig. 8(b)	0.01	0.01	0.01	1	1	0.5	0	(a'') in Fig. 7	Diagonal weave
Fig. 8(c)	0.01	0.01	0.01	1	1	0.5	0	(a'') in Fig. 7	Satin weave
Fig. 9(b)	1	1	0	1	1	$0.5r$	0	(a'') in Fig. 7	Plane weave

Table 1. Table 1: Parameters from Figs. 5 to 9. r is a random value in (0.5, 1] for each yarn. In Fig. 6 and 9(b), the initial amount of dye is kept constant during the simulation.